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Final Report for Grant NAG5-2458 from NASA to the University of Michigan

"IUE Observations of Solar System Objects"

Principal Investigator: John T. Clarke

Period of Performance: 1/1/88 - 12/31/94

This grant has supported IUE guest observations of solar system objects since 1988. There follows a list of approved programs which have been performed under this grant, a list of publications in refereed journals, and a list of abstracts of talks given at scientific meetings and invited colloquiua. Finally, there is a brief summary of the main scientific programs and results obtained over the seven years of this grant. It is with considerable sadness that we acknowledge the end of normal IUE observations, which have been particularly productive in the area of planetary science.

Approved IUE Programs under Grant NAG5-2458

Short Title and Investigators:	Year	Shifts Allotted
The Ionospheric Contribution to Jupiter's H Ly α Bulge, J. Clarke	11	2
Io's Atmosphere through Particle Excitation in Eclipse, J. Clarke, J. Luhmann, J. Ajello	11	2
Doppler Imaging of Aurora on Jupiter and Saturn, J. Clarke, M. Hudson	11	4
Doppler-shifted H Ly α Emission from Jupiter's Aurora, J. Clarke	12,13	5
Jupiter's Equatorial H Ly α Line Profile, J. Clarke, R. Gladstone, S. Chakrabarti	12,13	5
Saturn's Aurora at Solar Maximum, J. Clarke	13	3
IUE/ROSAT Coordinated Observations of Jupiter's Aurora, J. Clarke, H. Waite, F. Bagenal	13	4
Earth Auroral Observations with IUE, S. Chakrabarti, R. Gladstone, J. Clarke	13	2
Emission Line Profiles from Jupiter and Saturn, J. Clarke, R Gladstone	14	3
FUV and IR Observations of Jupiter's Aurora, J. Clarke, M. Peterson, W. Harris	14	4
Outer Solar System Targets of Opportunity, J. Clarke, M. McGrath	14	2
Ultraviolet Emissions from Saturn and Uranus, M. McGrath, J. Clarke, W. Moos, P. Feldman, D. Strobel	14	6
H Ly α Dayglow Emission Line Profile from Saturn, J. Clarke, M. McGrath, R. Gladstone, L. Ben Jaffel, R. Prangé, G. Ballester	15	2
Auroral and Dayglow Emissions of Saturn and Uranus, M. McGrath, J. Clarke, W. Moos, P. Feldman, and D. Strobel	15	7
Observation of the Shoemaker-Levy / Jupiter Collision W. Harris, G. Ballester, J. Clarke, M. Combi, R. Prangé, D. Rego, R. Gladstone	16	38

IUE-Related Refereed Publications Under Grant NAG5-2458

12. "The Jovian Aurora: Electron or Ion Precipitation?", H. Waite, J. Clarke, and T. Cravens, **J. Geo. Res., 93**, 7244, 1988.

13. "IUE Observations of Neptune for H Lyman-α Emission", J.T. Clarke, **Geo. Res. Lett., 15**, 701, 1988.

14. "Ionospheric Dynamo Theory for Production of Far Ultraviolet Emissions on Uranus", M. K. Hudson, J.T. Clarke, and J.A. Warren, **J. Geo. Res., 94**, 6517, 1989.

15. "Deuterium Lyman α Observations of Venus with IUE", J.-L. Bertaux and J.T. Clarke, **Nature, 338**, 567, 1989.

16. "Doppler-shifted H Ly α Emission from Jupiter's Aurora", J.T. Clarke, J. Trauger, and H. Waite, **Geo. Res. Lett., 16**, 587, 1989.

17. "Detection of H_3^+ on Jupiter", P. Drossart, J.P. Maillard, J. Caldwell, S.J. Kim, J. Watson, W. Majewski, J. Tennyson, S. Miller, S. Atreya, and J. Clarke, **Nature, 340**, 539, 1989.

18. "Center to Limb Variation in Jupiter's H Ly α Emission", J. Clarke and R. Gladstone, **J. Geo. Res., 95**, 21281, 1990.

19. "Jupiter's Dayglow H Ly α Emission Line Profile", J.T. Clarke, G.R. Gladstone, and L. Ben Jaffel, **Geo. Res. Lett., 18**, 1935, 1991.

20. "HI Ly-α Emission from Saturn (1980-1990)", M.A. McGrath and J.T. Clarke, **J. Geo. Res., 97**, 13691, 1992.

21. "Pluto's Extended Atmosphere: an Escape Model and Initial Observations", J.T. Clarke, S.A. Stern, and L.M. Trafton, **Icarus, 95**, 173, 1992.

22. "Variability in the Outer Planet Aurora", J.T. Clarke, *COSPAR Symp. S.5*, **Adv. in Sp. Res., vol. 12, no. 8,** p. 137, 1992.

23. "The Lyman alpha Bulge of Jupiter: the Effects of Line Broadening", L. Ben Jaffel, J.T. Clarke, R. Prangé, G.R. Gladstone, and A. Vidal-Madjar, **Geo. Res. Lett., 20**, 747, 1993.

24. "ROSAT Observations of the Jupiter Aurora", J.H. Waite, F. Bagenal, F. Seward, C. Na, G. R. Gladstone, T.E. Cravens, K.C. Hurley, J.T Clarke, R. Elsner, and S.A. Stern, **J. Geo. Res., 99, A8**, 14799, 1994.

25. "HST UV Spectral Observations of Io Passing into Eclipse", J.T. Clarke, J. Ajello, J. Luhmann, N. Schneider, and I. Kanik, *J. Geophys. Res., Planets , 99, E4*, 8387 (1994).

26. "Analysis of Jovian Auroral H Ly-α Emission (1981-1990)", W.M. Harris, J.T. Clarke, M.A. McGrath, and G.E. Ballester, submitted to **Icarus**, 1994.

27. "HST/GHRS Observations of the Interplanetary Medium Downwind and in the Inner Solar System", J.T. Clarke, R. Lallement, J.-L. Bertaux, and E. Quemerais, submitted to **Astropys. J.**, 1994.

28. "Far-Ultraviolet Emissions During the Impact of Comet Shoemaker-Levy 9 with Jupiter", G. Ballester, W. Harris, R. Gladstone, J. Clarke, R. Prangé, M. Combi, S. Budzien, C. Emerich, D. Hall, A. Talavera, M. Vincent, T. Livengood, M. McGrath, P. Feldman, D. Strobel, D. Rego, L. BenJaffel, and S. Miller, submitted to **Geo. Res. Lett.**, 1995.

29. "A Comprehensive IUE Study of UV Phenomena Related to the Collision of Comet Shoemaker-Levy (1993e) with Jupiter", W. Harris, G. Ballester, S. Budzien, T. Livengood, R. Prangé, M. McGrath, C. Emerich, A. Talavera, G. Fireman, D. Hall, M. Combi, L. Woodney, M. Vincent, K.-L. Jessup, J. Clarke, and R. Gladstone, submitted to **Science**, 1995.

IUE-Related Abstracts of Talks Under Grant NAG5-2458

"Outer Planet Aurora and Airglow: Recent Developments", J.T. Clarke and F. Bagenal, invited talk at *IAGA Meeting*, Exeter UK, July (1989).

"Jupiter's Atmospheric Spatial Variations Determined from H Ly α Emission", J.T. Clarke and G.R. Gladstone, *B.A.A.S., 21*, 942 (1989).

"Near-UV Reflectivity of Two Hemispheres of the Pluto-Charon System", E. Barker, A. Stern, N. Brosch, J. van Santvoort, J.T. Clarke, R. Gladstone, and L. Trafton, *B.A.A.S., 21*, 986 (1989).

"Observations of Aurora on the Giant Planets", J.T. Clarke, invited review at Fall AGU meeting, *EOS, 70*, 1172 (1989).

"Physical Underpinnings of Jupiter's Aurora", J.T. Clarke, colloquium at NASA Goddard Space Flight Center, January (1990).

"Variability in the Outer Planet Aurora", J.T. Clarke, invited review at *COSPAR Symp. S.5*, the Hague June (1990).

"Jupiter's Equatorial H Ly α Emission Line Profile", J.T. Clarke and G.R. Gladstone, *B.A.A.S., 22*, 1069 (1990).

"HI Ly α Emission from Saturn (1980-1990)", M.A. McGrath and J.T. Clarke, *B.A.A.S., 22*, 1072 (1990).

"H Ly α Emission from Saturn: Variations over 1980-1990", J.T. Clarke and M.A. McGrath, *EOS, 71*, 1483 (1990).

"Proton Precipitation at Jupiter", J.H. Waite, D. Curran, and J.T. Clarke, *EOS, 72*, 184 (1991).

"UV and IR Observations of Jupiter's Aurora", J.T. Clarke, invited talk at spring AGU, *EOS, 72*, 185 (1991).

"Ultraviolet Observations of Planetary Atmospheres", J.T. Clarke, invited colloquium, Dept. of Physics and Astronomy, University of Toledo, October (1991).

"The Lyman Alpha Bulge of Jupiter: Effects of Non-Thermal Velocity Field", L. Ben Jaffel, J.T. Clarke, G.R. Gladstone, R. Prange, B.R. Sandel, A. Vidal-Madjar, and R.V. Yelle, *B.A.A.S.*, *23*, 1135 (1991).

"Jupiter's H Ly α Emission Line Profiles", J.T. Clarke, G.R. Gladstone, and L. Ben Jaffel, *B.A.A.S.*, *23*, 1145 (1991).

"Observing Pluto's Extended Atmosphere", J. Clarke, A. Stern, and L. Trafton, at *Pluto and Charon*, Flagstaff AZ, July (1993).

"EUVE Observations of Jupiter's Plasmasphere", R. Gladstone, H. Waite, D. Hall, W. Moos, P .Feldman, D. Strobel, M. McGrath, J. Clarke, F. Bagenal, N. Schneider, and D. Shemansky, *B.A.A.S.*, *25*, 1052 (1993).

"Analysis of Jovian Auroral Ly-α Emission Variability with the IUE Satellite Archives", W.M. Harris, J.T. Clarke, M.A. McGrath, *B.A.A.S.*, *25*, 1054 (1993).

"Early Results from the IUE Shoemaker-Levy Observing Campaign: Temporal Evolution of the FUV/NUV Albedo in the Impact Regions", W.M. Harris, and 17 co-authors incl. G.E. Ballester and J. T. Clarke, *B.A.A.S.*, *26*, 1591, (1994).

"Auroral Signature of the Interaction of Comet Shoemaker-Levy 9 with the Jovian Magnetosphere", R. Prangé, and 22 co-authors incl. J.T. Clarke and G.E. Ballester, *B.A.A.S.*, *26*, 1596, (1994).

"Observing the Impact of Comet Shoemaker-Levy with Jupiter using the IUE Satellite", W.M. Harris, and 27 co-authors incl. G.E. Ballester and J.T. Clarke, *B.A.A.S.*, *26*, 1597, (1994).

Summary of IUE Research Programs under Grant NAG5-2458

Jupiter and Saturn Equatorial Ly α Emission Line Profiles Observations of Jupiter with the SWSA in high dispersion have been published, comparing the low latitude H Ly α emission line profile on and off the "Ly α bulge" at the longitude of the central meridian (CML), near the limb of the planet, and at midlatitudes on the CML. All equatorial locations show line broadening beyond the IUE resolution of 0.14 Å. Models of the line profile have shown that resonant scattering (RS) of solar emission can account for the broadening if there is a ~ 1 % superthermal population in the bulge upper atmosphere with velocities of 5-10 km/sec. In the 14-16 years we obtained more observations of the bulge and mid-latitude regions, and we have compiled "best" spectra of these regions by shifting and co-addition for comparison with the models. In the 14th and 15th years we obtained 1 and 2 shift integrations on Saturn at low latitudes, respectively, and find that with the 14 hour exposure we can obtain a useful S/N in the line profile after subtraction of the geocoronal and interplanetary backgrounds. The Jupiter line profiles are now being modeled by post-doc Daniel Rego under a NASA Planetary Atmospheres program grant to the University of Michigan.

Doppler Imaging of Aurora on Jupiter and Saturn Jupiter auroral spectra at high dispersion show H Ly α emission both Doppler-shifted and broadened, with velocities of 10-20 km/sec. This surprising result could be due either to slow proton charge exchange, or resonant scattering of solar Ly α in a supersonic thermospheric wind. Observations in the 14th-16th years recorded both north and south aurora at a variety of latitudes, and we have observed at both auroral and anti-auroral longitudes. The main goal of the newer observations is to determine the dependence of the line broadening on auroral activity: the blue-shifted emission is correlated with the H_2 band brightness, and possibly the broadening as well. SWLA high dispersion spectra of Saturn's aurora to date have occurred at times when the aurora were faint, and without detecting Doppler-shifted emission.

IR/X-ray/FUV Observations of Jupiter's Aurora The observations of Jupiter's aurora in recent years have been scheduled to be nearly simultaneous with IRTF and CFHT observations of 7.8 μ CH_4 emissions and 2.1 - 4 μ emissions of H_2 (quadrupole) and H_3^+ emissions from Jupiter's aurora. The detection of H_3^+ on Jupiter is the first time that this molecule has been detected outside of the laboratory. Coordinated observations at times of IRTF/CFHT observations at 2 and 4 μ have been performed, as well as IUE observations during both ROSAT WFC all-sky survey and pointed observations with the WFC and PSPC. ROSAT detected X-rays from Jupiter with both the PSPC and HRI detectors at times when simultaneous IUE spectra showed moderately bright aurora. The X-ray/IUE work has been published with the ROSAT PI, H. Waite, as first author, and the first H_3^+ observations were published with P. Drossart as first author.

Saturn and Uranus Ly α Emissions Observations of Saturn's dayglow H Ly α emission over the past solar cycle have now been published in JGR: Saturn's emission shows variability similar to that of Jupiter, and in phase with the solar activity, but with a greater amplitude than the solar Ly α flux! Unlike Jupiter and Saturn, Uranus has previously shown no correlation with solar activity: if this trend continues over a complete solar cycle, it will imply a fundamentally different production process than on Jupiter and Saturn. New observations of both Saturn and Uranus have been made into 1993, in collaboration with M. McGrath. These data have been reduced by L. Woodney, and a draft paper is being revised for publication.

Variation of the Solar Lyman α Line Profile with Solar Activity Eight IUE SWSA high resolution spectra of the solar H Ly α line profile as reflected from the Moon has been made to date, in a program with M. Combi as PI. A six-hour integration was made during relatively

solar quiet conditions (i.e. a relative minimum in solar activity and H Ly α flux with solar rotation), and the other shifts covered a range of solar activity conditions. Although the spectrum is somewhat noisy due to the radiation level during the US 2 shift, it clearly shows the shape of the line and the self-absorbed center, and demonstrates the feasibility of using IUE for this purpose. we have just finished reducing the remaining data, and are analyzing these data for evidence of solar line profile changes with solar activity.

Spectra of Jupiter During Impacts of Comet Shoemaker-Levy 9 W. Harris and G. Ballester from the University of Michigan have led a coordinated effort of 3 US and 1 European IUE programs to make observations of Jupiter during the impacts of Comet Shoemaker-Levy 9 in July 1994. The combined program has consisted of 56 IUE shifts, including baseline observations before and after the impacts, and persistent spectroscopy during the week of impacts. This has been one of the largest IUE observing programs to date, and the largest solar system program to date. The observations included spectra of the Io plasma torus, Jupiter's polar aurora, Jupiter's equatorial airglow, emission features from the impact sites, and the far-UV and near-UV albedos of the impact sites as functions of time. While little change was observed in the Io torus emissions, Jupiter's aurora were fainter than normal, the impact sites appeared very dark with decreasing albedo over the first 4-5 hours after the impacts, and emission was detected from two impact sites at the times of impacts. The initial results of these observations have been presented at the IAU General Assembly and DPS meetings over August-October 1994. Two papers reporting the overall program (Harris et al.) and the emissions observed from the impact sites (Ballester et al.) are nearly ready for submission at this time (early Jan. 1995). A large amount of additional reduction and analysis will be required to fully determine the changes in the Jupiter system observed with the IUE.